SAND2013-6561 C
Unlimited Release
July 2013

Potential LEU Encumbrances and Alternatives for the U.S. Production of Tritium for National Security Purposes

July 26, 2013

D.K. Lartonoix[1,2]

Abstract

The availability of tritium is essential to the U.S. nuclear weapons stockpile and any potential legal or policy issues impeding its production could have potentially drastic and far-reaching effects on national security. Specifically, potential encumbrances on low-enriched uranium (LEU) used in the tritium production process have been identified. The legality of these potential encumbrances has been explored and alternatives are suggested should the current production methods ultimately prove to lack long-term viability.

---

[1] The views expressed herein are those of the author and do not represent the views of Sandia National Laboratories.

[2] Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000. SAND 2013-6561C.

Introduction

Tritium is an essential component of nuclear weapons (NW) and, therefore, instrumental to national security. Tritium is radioactive and decays with a half-life of approximately 12 years, it is not found in significant quantities in nature and must be replaced periodically as weapons in the stockpile age. Historically, heavy water reactors (HWRs) at the Savannah River Site (SRS) have produced tritium for the nation's NW complex, but were shut down for safety concerns in 1988. Since then, U.S. tritium production has been minimal, consisting of specific short-term measures and tritium recycling from decommissioned warheads. Because these methods of replenishment are unsustainable and potentially insecure in the long term, a viable tritium supply must be devised. The most critical component of this analysis involves surveying potential large-scale tritium production alternatives and their associated likelihood of future utilization.

Overview - Current U.S. Production of Tritium

The Department of Energy (DOE) has contracted with Tennessee Valley Authority (TVA), a federally-owned utility corporation created by Congress during the Great Depression, to irradiate Tritium Producing Burnable Absorber Rods (TPBARs) in TVA's Watts Bar I Nuclear Generating Station for tritium production. Future or backup plans may also include tritium production at two other TVA reactors, Seqouyah-1 and -2, but these reactors are not currently being used for such purposes. Upon sufficient irradiation time and during the reactor refueling outage, the TPBARs are removed from the reactor and transported to DOE's Tritium Extraction Facility (TEF) at SRS, where the tritium is removed and processed (see "*Tritium Production Details, Alternative Methods, and Likelihood of Future Use"*).

As with all commercial nuclear power plants in the U.S., Watts Bar I (and Sequoyah-1 and -2) is fueled with low-enriched uranium (LEU) (typically 3 to 4% uranium-235). Because natural uranium consists of less than 0.7% U-235, the fissile isotope of uranium necessary for fission in most nuclear reactors, mined uranium must be enriched to the required percent. Currently, there are few companies in the U.S. that are licensed and have the capability to perform such uranium enrichment for commercial nuclear power fuel. According to the DOE, the only such company legally allowed to provide fuel to TVA to power Watts Bar I and produce tritium is the United States Enrichment Corporation (USEC).[2]

USEC

Privatized as part of the Energy Policy Act of 1992, USEC was contracted to operate the Paducah Gaseous Diffusion (PGDP) uranium enrichment plant in Paducah, KY, and the Portsmouth Gaseous Diffusion Plant in Piketon, OH, for the federal government.[3] The Piketon plant would eventually be shuttered and all enrichment operations consolidated at the Paducah plant. Although PGDP produced special nuclear material (SNM) for defense NW purposes many decades before, it was now tasked with enriching uranium to a much lower level to be used in commercial nuclear power plants for civilian electricity production.

Built in the 1950s, PGDP grew to be outdated and inefficient by the late 1990s. Although still functionally viable, operational costs (notably electricity consumption) at PGDP proved high in comparison to newer plants like URENCO's Eunice, NM, centrifuge enrichment facility. USEC found it difficult to compete on the LEU market; URENCO's centrifuge enrichment plant required approximately one-sixtieth as much electricity to run and, benefitting from significantly lower operational costs.[4] PGDP subsequently lost significant market share in the early 2000s.

---

[2] DOE (U.S. Department of Energy), Interagency Review of the Nonproliferation Implications of Alternative Tritium Production Technologies Under Consideration by the Department of Energy - A Report to the Congress, July 1998.

[3] USEC, Inc., "USEC - The Company – History," accessed July 2013, http://www.usec.com/company/history.

Recognizing gaseous diffusion as requiring too much electricity to be economically viable and competitive on the open market, USEC began exploring plans for a centrifuge-based enrichment facility located on the grounds of the retired Portsmouth Gaseous Diffusion Plant in Ohio. USEC's Lead Cascade Demonstration Program (LCDP), licensed by the Nuclear Regulatory Commission (NRC) in 2004, featured AC100 centrifuges, purportedly the most advanced and energy efficient centrifuges in the world. The LCDP, meant to demonstrate the feasibility of using AC100 centrifuges on a commercial scale, began as a small-scale operation. As the demonstration proved more and more successful, additional cascades of centrifuges were added to the line, expanding the size and capability of the facility. In 2007 the NRC licensed the LCDP facility for commercial operations, at which point USEC redesignated the plant the American Centrifuge Project (ACP).[5]

Although proving to be technologically successful, the ACP began to suffer from political opposition. USEC, upon being spun-off from government ownership, continued to be the only U.S.-owned commercial enrichment company. As gaseous diffusion proved to be uneconomical and the company began investing in centrifuge enrichment, USEC uniquely required research and development (R&D) funds provided by the U.S. Congress to keep the ACP afloat. During the demonstration phase of LCDP/ACP, no saleable product was being produced. Because it was seen as critical to national defense to retain an indigenous enrichment capability, Congress obliged and continued to provide yearly installments. However, as the program shifted from demonstration phase to commercial production phase, a larger commitment was needed. In 2008, USEC applied for a $2B loan under the DOE Loan Guarantee Program, established under the Energy Policy Act of 2005, but was rebuffed.[6] Instead, three years later, DOE answered with a counterproposal. Under the new agreement, USEC would continue to operate ACP as a R&D venture. USEC would receive two years of operational support funding, but not the loan guarantee, which would remain “pending” during this time. No assurances were given to USEC that a successful completion of the additional R&D period would result in approval of the loan guarantee.

DOE preferred to delay the decision on a loan guarantee, in part, over concern for USEC's financial status. The company's stock had dropped significantly since its initial public offering approximately a decade prior, Moody's Investor Services had downgraded its ratings for USEC in late 2009, and increasing competition from other enrichment ventures in the U.S. were cited as reasons to doubt the viability of USEC as a whole.[7, 8] USEC had been heavily investing its own financial resources on a project that, looked as if it may never get off the ground. The concern of financial stability perhaps stemmed from USEC's initial privatization. Under the 1992 Act, USEC became a private entity and was contracted solely to operate Paducah and Portsmouth; the government retained ownership of the plants themselves. As merely a contractor and operator,

---

[4] URENCO, “URENCO - Centrifuge cascades,” accessed July 2013, http://www.urenco.com/page/20/Centrifuge-cascades.aspx.

[5] U.S. Nuclear Regulatory Commission, “USEC Inc. Gas Centrifuge,” accessed July 2013, http://www.nrc.gov/materials/fuel-cycle-fac/usecfacility.html.

[6] USEC Inc., “USEC – The American Centrifuge – The Plant – Funding,” accessed 2013, http://www.usec.com/american-centrifuge/what-american-centrifuge/plant/funding.

[7] MarketWatch, Inc., “USEC Inc. – Overview,” accessed July 2013, http://www.marketwatch.com/investing/stock/usu.

[8] The Associated Press, 2009, “Moody's downgrades USEC ratings,” *The Seattle Times*, December 18, 2009, http://seattletimes.com/html/businesstechnology/2010544090_apususecratings.html.

USEC was spun off with no assets in hand and little financial liquidity. Subsequently, USEC lacked enough collateral to sufficiently back a $2B loan guarantee, raising significant doubts in DOE and Congress whether granting the loan request was advisable, especially in light of the recent backlash pertaining to the Solyndra failure after having received a similar loan guarantee.[9]

Perhaps the only leverage that USEC had in the fight for the loan guarantee was that it remained the only U.S.-owned enrichment company in the U.S. The other two domestic commercial uranium enrichment facilities conceived at the time were being developed by Areva, a French company, and URENCO, a Dutch/German/British company. According to the DOE, LEU enriched by either company for use in U.S. commercial nuclear reactors would be ineligible for tritium production.[10]

An Interagency Review conducted by DOE in 1998 and reported to Congress established the critical link between tritium production for U.S. defense purposes and the debate surrounding the Congressional funding and pending loan guarantee of USEC's ACP. DOE outlined its official position on several key facets of the (at this point, future) decision to use a civilian commercial nuclear power plant to produce tritium for use in NWs. First, DOE asserts that the proposed practice is indeed allowable. "The review concluded…that the use of CLWRs [commercial light-water reactors] for tritium production was not prohibited by law or international treaty."[11] This particular statement was in response to critics that claimed the practice violated the long-held tenant of U.S. nonproliferation policy of military-civilian separation of nuclear facilities. DOE went on to point out that historically "there had been numerous exceptions to the practice of differentiating between U.S. and civilian military facilities" and briefly outlined several, from medical isotopes produced in defense reactors to prior examples of the use of the U.S. defense enrichment program for civilian purposes. Simply put, "the civil/military separation has never been absolute."[12] Later, the National Defense Authorization Act for Fiscal Year 2000 would expressly give the DOE the legal authority to use TVA's Watts Bar and Sequoyah for the production of tritium.[13] Second, DOE concluded that "[tritium] is not classified as a special nuclear material and is therefore not subject to the prohibition in the Atomic Energy Act of 1954, as amended, on the use of such materials for nuclear explosive purposes if produced in a commercial light water reactor."[14] Based on these two assertions the legal basis for the decision to proceed with tritium production in a civilian reactor, as interpreted by DOE, was declared. However, a third major conclusion of the report, although not largely relevant or concerning in 1998, has become significant in recent years:

> Certain U.S. bilateral agreements for nuclear cooperation prohibit the use of fuel and equipment imported under those agreements from being used for nuclear explosives. In pursuing the CLWR option, DOE would assure its trading partners that no foreign nuclear fuel or equipment supplied that was subject to such restrictions was being used for tritium production in a CLWR.[15]

---

[9] Rachel Weiner, "Solyndra, explained," *The Washington Post*, June 1, 2012, http://www.washingtonpost.com/blogs/the-fix/post/solyndra--explained/2012/06/01/gJQAig2g6U_blog.html.

[10] Department of Energy, Nonproliferation Implications of Alternative Tritium Production

[11] Ibid.

[12] Ibid.

[13] Public Law, 106-65, 1999, *National Defense Authorization Act for Fiscal Year 2000,* 113 Stat. 512, October 5, 1999.

[14] Department of Energy, Nonproliferation Implications of Alternative Tritium Production

[15] Ibid.

Clarification of DOE's position on the particular subject was not presented nor did DOE elaborate on "certain U.S. bilateral agreements." DOE administratively limited itself to using domestically-enriched fuel for producing tritium. This was not concerning at the time because DOE also claimed that "ample supplies" existed for such a purpose.[16]

With DOE's report outlining the necessity for the use of only domestically-enriched fuel for the production of tritium, USEC by default was designated as the sole supplier of enrichment services to Watts Bar I. Congress and DOE used this line of reasoning as justification of the continuing financial support of R&D funding for USEC's ACP. When USEC's R&D agreement expired in 2010, Congress lacked a clear plan forward for ACP. Forced to again reconsider the $2B loan guarantee, the substance of DOE's 1998 report requiring a domestic source of uranium enrichment began to be questioned by decision makers hoping to avoid funding ACP by simply purchasing reactor fuel from a U.S.-located, foreign-owned supplier. As Areva's enrichment plant plans had stalled, only URENCO was left as an option.

Congressional Research Service Involvement

In May 2012, Representative Ed Markey (D-MA) requested that the Congressional Research Service (CRS) provide background information regarding potential legal restrictions originating from U.S. and international agreements governing the use of uranium to produce tritium. Specifically, Markey wanted insight and guidance from an impartial source as to whether URENCO-enriched fuel could legally be used in Watts Bar I. The impetus for the request to CRS stemmed from Markey's desire to restrict or cut Congressional funding to USEC. If the U.S. was not legally required to domestically enrich uranium for tritium production, Markey would prefer that DOE purchase URENCO fuel instead of funding USEC's enrichment capabilities. Markey has for many years been opposed to Congressional financial support for USEC.[17]

Two CRS memorandums resulted from the Markey inquiry, one from the policy perspective and one from the legal perspective. The policy memo, dated May 15, 2012, essentially amounts to an initial exploration of the subject. The brief outlined the general issue at hand, URENCO vs. USEC, and listed several likely alternative fuel options without going into much depth.[18] The legal assessment, however, offers considerably more detail in its description of the governing factors pertaining to the source of enriched uranium for tritium production.

The legal assessment conducted by CRS, although detailed and thorough, acknowledges its own deficiencies before outlining its assessment of LEU use for tritium production. It notes "the time constraints on this request, the lack of case law or legal authority related to this question, the sensitive nature of the agreements, the limited amount of reliable and publicly available information relating to negotiations and discussions between the U.S. and the applicable foreign nations, and the resulting difficulties in reaching any definitive interpretive conclusions."[19] Each of these statements are critical shortcomings, but the assessment attempts to contribute to the context of the debate in a meaningful way. Furthermore, due to the nature and sensitivity of the subject, potentially useful information may be kept confidential by the U.S. government. CRS noted a difficulty in obtaining DOE's justification for its policy of requiring only domestic-enriched uranium for tritium production and assumed that it had not been released publicly. This led CRS to conclude that "[i]t is unclear whether the DOE position is one based on what it judges to be legal requirements, policy considerations, or additional unspoken or informal understandings."[20] Clearly, CRS recognized significant difficulty and uncertainty pertaining to the subject of the request, but nevertheless attempted to provide background for Markey's request.

---

[16] Ibid.

[17] Deirdre Shesgreen, "House reaffirms USEC funding," *Chillicothe Gazette*, July 11, 2013, http://www.chillicothegazette.com/article/20130710/NEWS01/307100027/House-reaffirms-USEC-funding.

[18] Mark Holt and Mary Beth Nikitin, "Potential sources of nuclear fuel for tritium production," *Congressman Ed Markey Official Website,* May 15, 2012, http://markey.house.gov/sites/markey.house.gov/files/documents/2012_0515_CRS_TritiumFuelOptions.pdf.

[19] Todd Garvey, "Peaceful Use Restrictions on Uranium Enriched at the Urenco Enrichment Facility," *Congressman Ed Markey Official Website,* May 21, 2012, http://markey.house.gov/sites/markey.house.gov/files/documents/2012_0521_CRSTreaty.pdf.

Perhaps the most useful aspect of the CRS legal report is its identification and general description of the international agreements pertaining to nuclear technology by which the U.S. may be bound in searching for a fuel source for tritium production. Among those most likely to be applicable, the 1992 Washington Agreement and the 1996 Euratom Agreement have been singled out.

The 1992 Washington Agreement

The 1992 Washington Agreement[21] between the U.S. and the governments representing the ownership of URENCO (UK, Netherlands, and Germany) formed the international legal basis for developing URENCO's uranium enrichment facility in Eunice, NM. The agreement, necessary because any U.S. nuclear-related collaboration on a commercial basis with foreign entities must be solely peaceful in nature according to the Atomic Energy Act Section 123 and 42 U.S.C. §2153,[22] which governs the conditions by which European-based URENCO can "transfer" or import nuclear technology into the U.S. for use by its American-based subsidiary. Specifically, Article III of the agreement states:

> Any ETC [company] Centrifuge Technology, Operations Technology, equipment and components transferred into the United States subject to this Agreement, each Installation, any Nuclear material in an Installation, any special nuclear material produced through the use of such technology, any special nuclear material produced through the use of such special nuclear material, and any data generated at an Installation that is designated Restricted Data while such data is under the jurisdiction of the United States Government or any of the Four Governments shall only be used for peaceful, non-explosive purposes.[23]

This article forms the basis surrounding the debate of using enriched uranium to produce tritium for U.S. NWs. Several clauses are established that prevent the implementer from contributing to NW-related activities, and the central focus of the CRS legal brief is to judge the applicability to the U.S. tritium production program. Because the centrifuge technology, operations technology, and data generated at the site are non-contributors to the tritium program, these factors were not considered; the interpretive difficulties surround the use of SNM produced at the enrichment facility. The phrase "any special nuclear material," dubbed first-generation material by the CRS author, most commonly refers to uranium, which clearly is prohibited from direct use in a nuclear weapon per this statute.[24] DOE has concluded[25] and the CRS legal assessment noted[26] that tritium is not classified SNM, which possibly negates the relevancy of this clause of Article III. The second clause limiting the use of "any special material produced through the use of such special nuclear material" (dubbed second-generation material) most commonly refers to plutonium produced in a uranium-fueled reactor. As such, URENCO-enriched uranium is prohibited from fueling a reactor to make plutonium for use in NWs according to the agreement. However, the same classification of tritium as non-SNM may render the clause non-applicable; however, CRS outlines two possible countering interpretations.

---

[20] Ibid.

[21] Secretary of State for Foreign and Commonwealth Affairs, Agreement between the Government of the United States of America and the Four Governments of the French Republic, the United Kingdom of Great Britain and Northern Ireland, the Kingdom of the Netherlands, and the Federal Republic of Germany regarding the Establishment, Construction and Operation of Uranium Enrichment Installations using Gas Centrifuge Technology in the United States of America ["1992 Washington Agreement"], 1992, http://www.official-documents.gov.uk/document/cm80/8047/8047.pdf.

[22] Todd Garvey, "Peaceful Use Restrictions on Uranium"

[23] Secretary of State for Foreign and Commonwealth Affairs, *Establishment, Construction and Operation of Uranium Enrichment Installations*

[24] Todd Garvey, "Peaceful Use Restrictions on Uranium"

The CRS analysis involves describing two distinct interpretations of the aforementioned phrases, one legally "broad" interpretation and one "narrow" interpretation.[27] Without any legal precedent and lacking relevant case law, CRS is relegated to describing and outlining each case. The narrow interpretation attempts to stick close to the letter of the statue. Under this interpretation, only uranium, plutonium, and other specific SNM would be subject to the non-explosive use restriction; tritium, as a nuclear material but specifically non-SNM, would be excluded and no part of the Agreement would apply here. This interpretation concludes that URENCO-enriched fuel be used to power Watts Bar I during tritium production. Legally permitting URENCO, a foreign-owned company, to produce LEU for tritium production conflicts with the stated but unsubstantiated DOE position requiring domestically-enriched LEU for such purposes. In contrast, a broad interpretation of the Agreement asserts that no material derived from URENCO-enriched LEU may be used in a nuclear weapon "no matter how attenuated the eventual non-peaceful use is from URENCO's original enrichment."[28] In other words, tritium is eventually produced from statute-governed material (URENCO LEU) and may only be used for peaceful purposes. Because first-generation material may not be used to produce second-generation material for non-peaceful purposes, the broad interpretation argues that no n^th^-generation material, by extension, may either. This conclusion precludes URENCO fuel from being used in TVA to produce tritium. With CRS noting shortcomings with both interpretations, a clear legal resolution is not obvious.

The 1996 Euratom Agreement

The Euratom Agreement is the second pertinent international agreement identified by the CRS brief and, though governing the same exchange with the same parties as the Washington Agreement, contains its own distinct language. The relevant language requiring interpretation in Article 7 states:

> Non-nuclear material, nuclear material and equipment transferred pursuant to this agreement and special fissionable material used in or produced through the use of such items shall not be used for any nuclear explosive device or for any military purpose.[29]

As with the Washington Agreement, the wording of the Euratom Agreement is open to interpretation. Because the development of the URENCO uranium enrichment facility does not involve the actual transfer of nuclear or non-nuclear material, the only contested portion of the Article involves the "equipment." The centrifuges being transferred to construct the URENCO facility may logically constitute "equipment," but Article 21 of the Agreement narrowly defines

---

[25] Department of Energy, Nonproliferation Implications of Alternative Tritium Production

[26] Todd Garvey, "Peaceful Use Restrictions on Uranium"

[27] Ibid.

[28] Ibid.

[29] U.S.-European Atomic Energy Community, Agreement for Cooperation in the Peaceful Uses of Nuclear Energy Between the European Atomic Energy Community and the United States of America ["Euratom Agreement"], 1996, http://nnsa.energy.gov/sites/default/files/nnsa/inlinefiles/Euratom_123.pdf.

equipment to strictly mean "any reactor as a complete unit."[30] As a result, the centrifuges to be installed are not deemed "equipment" and the applicability of the entire Euratom Agreement to the URENCO LEU for tritium production debate is called into question.

However, CRS notes that DOE disagrees with this assessment. DOE and other federal employees have been quoted saying that treaty obligations prevent the use of URENCO uranium to produce tritium.[31] With no available DOE analysis or official position statement, the reasons behind DOE's interpretation are unclear.

Current State of USEC, URENCO, TVA, and Tritium Production in the U.S. (July 2013)

USEC's lease of PGDP from the federal government was scheduled to conclude at the end of May 2012. To continue operations at PGDP for an additional year, a controversial arrangement was devised by several parties. In the middle of May 2012, nearing the deadline, the DOE agreed to provide government-owned depleted uranium tails to USEC through the Bonneville Power Administration (BPA), a DOE-owned company that sells electricity produced through federally owned projects including hydroelectric dams in the U.S. Northwest. Under the agreement, BPA contracted with USEC to re-enrich the tails and then sold a portion of the resulting LEU to TVA for reactor fuel. The arrangement allowed for the continued operation of PGDP by USEC for an additional year.[32]

The following year, negotiations between USEC and DOE did not result in an additional extension.[33] In May 2013, USEC's lease of PGDP officially expired. Even though "USEC expects to continue operations at the site into 2014 in order to manage inventory, continue to meet customer orders and to meet the turnover requirements of its lease with DOE,"[34] activities have shifted to a closeout phase.

Even before the failure to renegotiate a deal with USEC, DOE started to search for a replacement contractor for the Paducah site. A "Request for Expressions of Interest" call went out in February 2013 for "lease or purchase of DOE Paducah Gaseous Diffusion Plant (PGDP) facilities or land near Paducah, Kentucky, either to continue the use of the facilities to enrich uranium, or separately for other nuclear fuel industry applications."[35] The call also listed the potential for inclusion of the large stocks of depleted uranium currently stored at PGDP in the deal.[36] Approximately nine entities (companies, joint ventures), have expressed interest with DOE pertaining to the Paducah Site.[37] Details of the proposed plans or the identities of the interested parties have not commonly been released, as negotiations with DOE are ongoing. However, GE-Hitachi subsidiary Global Laser Enrichment announced it was one of the interested parties with hopes to use its Silex laser enrichment process on the depleted uranium stores.[38] A joint venture between International Isotopes Inc. and Advanced Process Technology Systems has also declared interest. Neither details of DOE's intentions for PGDP nor a timeline for any action has been released.

---

[30] Ibid.

[31] Todd Garvey, "Peaceful Use Restrictions on Uranium"

[32] USEC, Inc., *Five-Party Arrangement Extends Paducah Gaseous Diffusion Plant Enrichment Operations.* May 15, 2012, accessed July 2013, http://www.usec.com/news/five-party-arrangement-extends-paducah-gaseous-diffusion-plant-enrichment-operations.

[33] USEC, Inc., "USEC to Cease Enrichment at Paducah Plant," May 24, 2013, http://www.usec.com/news/usec-cease-enrichment-paducah-plant.

[34] Ibid.

[35] Federal Business Opportunities, "Request for Expression of Interest in DOE Paducah Gaseous Diffusion Plant," February 6, 2013, https://www.fbo.gov/index?s=opportunity&mode=form&id =ff41cfd2dd03365797d225a2773629a2&tab=core&_cview=1.

[36] Ibid.

[37] World Nuclear News, "Joint venture confirms Paducah interest," April 9, 2013, http://www.world-nuclear-news.org/ENF-Joint_venture_confirms_Paducah_interest-0904138.html.

[38] Ibid.

USEC's ACP is ongoing. Additional, short-term research and design funding was procured from Congress in 2012 and will expire at the end of 2013. USEC intends to "update the DOE loan guarantee application for the project during 2013."[39] Entering the closeout of PGDP, USEC appears to be resuming the push to build ACP.

Watts Bar I continues to produce electricity for the surrounding Tennessee counties as well as tritium for national defense needs. With 18-month fueling cycles, operating plans have been made several years into the future that account for the use of TPBARs. As previously mentioned, the DOE agreement in 2012 to provide USEC with an additional year of work yielded domestically-enriched LEU available for tritium production in TVA reactors. This stock of fuel will presumably be used in the upcoming fuel cycles at Watts Bar I to continue to produce power and tritium, as it is the only unencumbered fuel available. As long as DOE's prohibition of non-domestic enriched uranium remains in place, it is unclear where LEU fuel for Watts Bar I will come from once this finite stock is depleted.

Tritium Production Details, Alternative Methods, and Likelihood of Future Use

Although current methods are progressing and are technically sufficient, LEU fuel sources for use in Watts Bar I may prove to be unsustainable. Because the lack of tritium represents a possible threat to the efficacy of the U.S. nuclear deterrent and therefore national security, alternative tritium production options must be explored. Several methods of tritium production exist, each having specific advantages and disadvantages. Currently, light water reactors (LWR), HWRs, and particle accelerators represent the most likely path to viable tritium production in the U.S. Liquid metal reactors (LMR) and high temperature gas-cooled reactors (HTGCR) also hold technological promise, but likely will not be feasible in the near term. Science is attempting to prove the technical merits of using alternative or "exotic" means for tritium production.

The experience level within the U.S. designing, operating, and maintaining tritium production options varies widely, a factor that likely will impact any future undertakings. Also, while only a few reactors of various types currently exist which could presently reasonably accommodate tritium production, pursuing other options would require building a new facility entirely. As a result, several aspects and characteristics of each system will certainly have an impact on the respective likelihood of future use.

Light Water Reactor (LWR)

Tritium can be formed in a LWR by exposing lithium-6 (Li-6) to a neutron flux of any energy according to the following reaction:

$$ {}^{6}_{3}Li + {}^{1}_{0}n \rightarrow {}^{4}_{2}He + {}^{3}_{1}T \qquad (1) $$

However, natural lithium is less than 8% Li-6 and, therefore, needs to be enriched in Li-6 for efficiency and ease of tritium production.[40] A similar and beneficial reaction from Li-7 can also lead to the production of tritium, but requires a high-energy neutron to initiate:

---

[39] USEC, Inc., "USEC Provides American Centrifuge Update," March 18, 2013. http://www.usec.com/news/usec-provides-american-centrifuge-update-0.

[40] Office of Science Education, "Isotopes of the Element Lithium," *Jefferson Lab*, accessed June 18, 2013, http://education.jlab.org/itselemental/iso003.html.

$$ {}_{3}^{7}Li + {}_{0}^{1}n \rightarrow {}_{2}^{4}He + {}_{1}^{3}T + {}_{0}^{1}n \qquad (2) $$

A TPBAR is used to house the lithium being converted into tritium within the LWR core. Specifically, Type 316 stainless steel cladding tubes contain ceramic lithium aluminate ($LiAlO_2$) pellets and a Zircaloy-4 tritium “getter.” The “getter” captures, retains, and prevents diffusion loss of the tritium produced, and is nickel-plated to prevent oxidation of tube surface walls.[41] After formation, the tritium is trapped within the getter as a metal hydride for later extraction.

The presence of TPBARs within a PWR has only a minimal effect on reactor operations. However, some tritium diffusion through the cladding wall and into the coolant water has been observed, so care must be used to remain within tritium effluent regulatory limits.

Upon reactor shutdown and removal from the core, the TPBAR is transported to a specialized facility to separate tritium from the supporting materials. This extraction process removes tritium via chemical reaction. Upon further purification, the tritium can be packaged for transportation.

Tritium can also be produced in specific, non-commercial nuclear reactors that are typically geared toward research. Because research reactors are unique and might be more easily customized, there is the potential for tritium production modification to an existing reactor not originally built for that use. Such an arrangement would have to be made on a case-by-case basis with any such alterations largely based on original system characteristics.

Likelihood of Future Use – Light Water Reactor

LWR production of tritium is the only method currently being used in the U.S. and, as a result, the likelihood of future use in the short term is high. The LWR method is how tritium is produced in Watts Bar I reactor and extracted at SRS’s TEF. For the indefinite period, this is DOE’s plan to fill the tritium need for defense purposes.

Because of the aforementioned legal uncertainties, LWR production of tritium may not prove to be a long-term solution. Without a more secure source of enriched uranium, legal challenges may derail the current model. Alternative sources of uranium do exist, although few have been explored in enough depth to be considered very likely in the near term. The U.S. does maintain a quantity of highly-enriched uranium (HEU) that could potentially be downblended into LEU for use in LWRs to produce tritium. However, much of this HEU has been declared “surplus to U.S. defense needs” and stamped with presidential promise never to use for “weapons purposes.”[42] Legal interpretation may be necessary to resolve whether downblending to LEU for tritium production constitutes “weapons purposes.” Also the mechanism for removing this presidential guarantee is unclear. Furthermore, the HEU may have to be kept as a reserve for naval reactor fuel needs. This downblending process would likely need to be done at PGDP, thus encountering similar hurdles to the current process.

The reenrichment of DOE depleted-uranium stores also represents a potential option as DOE currently has a vast supply of depleted uranium that is not labeled with presidential or treaty encumbrances. However, an enrichment facility like PGDP would be needed.

USEC’s ACP facility, once completed and fully operational, would represent the only domestic source of enriched uranium if PGDP ends up being moth-balled. Enriching natural uranium, downblending HEU, or reenriching depleted uranium would each need to progress through ACP if no replacement operator for PGDP is arranged.

---

[41] D.D. Lanning, “Tritium Target Qualification Project,” December 1999, http://digitalcorpora.org/corp/nps/files/govdocs1/268/268707.pdf.

[42] Mark Holt and Mary Beth Nikitin, “Potential sources of nuclear fuel for tritium production”

Another potential fuel source for TVA reactors could come from the mixed-oxide (MOX) fuel fabrication facilities currently being explored at SRS. The facility would blend surplus weapons plutonium with uranium into a MOX form that could be fabricated into fuel elements to power reactors producing tritium. However, the material may have "weapons purposes" prohibitions on it that would preclude its use.[43] Implementing MOX fuel has been demonstrated in France,[44] however, no U.S. reactors currently use this fuel type. Also, the project has come under fire for being excessively expensive and constantly faces the threat of being halted.[45]

As a federally owned company, TVA's situation is relatively unique. The company's official website claims that "TVA has an obligation to and a long history of supporting the nation's security requirements."[46] This arrangement makes it unlikely that tritium production would be expanded to any of the other approximately 100 commercial nuclear reactors in the U.S.

Another possibility for tritium production is to use a non-commercial LWR. One candidate is the High Flux Isotope Reactor (HFIR), a research reactor located at Oak Ridge National Laboratory (ORNL). A a one-of-a-kind reactor built to supply isotopes for research and medical purposes, conduct materials experiments, and investigate neutron scattering phenomena, the HFIR offers several potentially attractive characteristics for tritium production. The HFIR operates with an exceptionally high neutron flux, which could lead to high Li-6 conversion rates. In addition, the geometry of HFIR, consisting of a cylindrical fuel region and a fuel-free center cavity, is convenient for Li-6 insertion and withdrawal. The HFIR configuration could present opportunities to measure or enhance production.[47] Though significantly different from using TPBARs in a commercial LWR, research reactors could offer a viable means of tritium production. Though no proposal has been made to use HFIR for tritium production, it is included to note capability.

Similarly, the Advanced Test Reactor (ATR), located at Idaho National Laboratory (INL), could also be used for tritium production. A research reactor originally built for materials testing and to produce isotopes for research and medical applications, ATR is customizable and operates at a high neutron flux. Its unique serpentine core shape and large test volume would be ideal for tritium production purposes. Over four decades of operational experience also lends a high degree of confidence in reactor functionality and adaptability.[48]

Heavy Water Reactor

Another tritium production method involves using a heavy water reactor (HWR), aptly named because it uses heavy water as a moderator. Heavy water, rather than (H_2O), contains hydrogen atoms that have absorbed an additional neutron ($^{2}_{1}H, deuterium$) and is signified as D_2O. When deuterated water absorbs an *additional* neutron, tritiated water (T_2O) is formed. The simplistic hydrogen absorption process can be described as:

---

[43] Ibid.

[44] Matthew L. Wald, "U.S. Moves to Abandon Costly Reactor Fuel Plant," *The New York Times,* June 25, 2013, http://www.nytimes.com/2013/06/26/us/us-moves-to-abandon-costly-reactor-fuel-plant.html?_r=0.

[45] Ibid.

[46] Tenessee Valley Authority, "Tritium Production at TVA," accessed June 20, 2013, http://www.tva.gov/news/tritium.htm#chronology.

[47] Oak Ridge National Laboratory, "The High Flux Isotope Reactor at ORNL," accessed June 18, 2013, http://neutrons.ornl.gov/facilities/HFIR/.

[48] Idaho National Laboratory, "Advanced Test Reactor," accessed June 18, 2013, http://www.inl.gov/research/advanced-test-reactor-research/.

$$^{1}_{1}H + ^{1}_{0}n \rightarrow ^{2}_{1}H \tag{3}$$

$$^{2}_{1}H + ^{1}_{0}n \rightarrow ^{3}_{1}H \tag{4}$$

The neutron absorption cross-section for deuterium is exceedingly small, only 0.52 millibarns (b),[49] so the production of appreciable amounts of tritium requires a reactor with a high neutron flux. Typically, this characteristic is also accompanied by reactor materials chosen to minimize parasitic neutron absorptions. Unlike tritium production via Li-6, any usable tritium must be extracted via isotopic separation, which is much more challenging than chemical extraction.

Likelihood of Future Use – Heavy Water Reactor

Being the first technology to fully demonstrate the production of usable amounts of tritium, the HWR experience and knowledge to establish an efficient manufacturing program are well established, though capabilities may have languished as no current reactors in the U.S. operate with a heavy water moderator. Prior projects could easily serve as models for a new construction HWRs, but the financial cost would be significant and highly uncertain.

HWRs are operated in foreign countries and successful tritium separation and removal has been demonstrated. Canada operates the world's largest tritium separation facility (Darlington Nuclear Generating Station).[50] Other countries operating HWRs include South Korea and India.

Cost should be considered, as the financial burden of utilizing a HWR for future tritium production is high. However, the level of experience, knowledge, and proof of viability present in the HWR method are not present with many other technologies. Rather than additional hurdles to be overcome, these HWR facets can stand to bolster confidence in new efforts at tritium production.

Accelerator Produced Tritium (APT)

Tritium production using a charged particle accelerator has also been investigated, though efforts in the U.S. have remained strictly in the research and design category. This method uses a particle accelerator to excite charged particles, typically protons, to very high energies and velocities. When an impact target is placed in the path of this proton beam, the charged particles violently collide with impact target atoms and release a large number of subsequent neutrons. These product neutrons form tritium in one of two ways. Throughout research and design efforts, a lithium-aluminum main target, based upon the same (n,T) reaction used to produce tritium in a LWR, has been proposed in parallel to research endeavors using a helium-3 (He-3) main target. As tritium decays into He-3, a He-3 main target subjected to neutrons would transform the He-3 back into tritium.

A lithium-aluminum main target subject to a stream of neutrons in an accelerator would function in a similar manner to a TPBAR in an LWR. Differences in the two processes occur at the initiation, but the end results are identical. The proton beam collides with a lead impact target to provide an "avalanche" of neutrons and additional charged particles. It has been estimated that a 1.6 GeV, 250 mA continuous wave beam incident on a lead target could produce a sizeable

---

[49] Alan, Munter, ed., "Neutron scattering lengths and cross sections," *National Institute of Standards and Technology*, November 23, 1999, http://www.ncnr.nist.gov/resources/n-lengths/elements/h.html.

[50] CNSC (Canadian Nuclear Safety Commission), *Evaluation of Facilities Handling Tritium*, February 2010. http://pbadupws.nrc.gov/docs/ML1029/ML102990087.pdf.

5×10^{16} n/cm^2/s thermal neutron flux for the conversion process.[51] While water is used to cool the lead and moderate the resultant neutrons, the neutrons interact with Li-6 to produce tritium in the same manner as described for a TPBAR. The tritium extraction process would be similar, relying on chemical differences in the byproducts to separate out the desired tritium. Like TPBARs, individual tubes containing the newly-formed tritium must undergo extraction on a batch system, tube by tube. Of additional concern, however, the lead impact target, now radioactive, requires special disposal handling.

Using a He-3 main target has also been investigated. For this setup, a tungsten impact target is struck by a proton beam to produce neutrons. The neutrons enter a tank of heavy water and react with He-3 contained within a continuously circulating system of piping within the tank according to the following reaction:

$$ {}^{3}_{2}He + {}^{1}_{0}n \rightarrow {}^{3}_{1}T + {}^{1}_{1}p \qquad (5) $$

This kind of target offers the considerable advantage that the thermal (2200 m/s) neutron absorption cross section for He-3 is 5333b versus 940b for Li-6, representing almost a six-fold increase in the reaction likelihood.[52] This difference could allow for tritium production at a lower flux or a higher rate of conversion at a higher flux.

A significant difference from other methods is the continuous feed of He-3 and removal of tritium (note: the sidestream of tritium would still contain He-3). After tritium and He-3 were separated in the product stream, the He-3 could be fed back into the system. Based on the use of a tungsten target and geometrical differences, there are fewer radioactive waste handling and disposal concerns when using a He-3 target.[53]

Likelihood of Future Use – Accelerator Produced Tritium

The prospect of APT offers several significant advantages that make the technology attractive. Foremost, several safety and environmental concerns stemming from using reactors to produce tritium are alleviated by APT. No fissile/fissionable materials are used in the APT process, negating the necessity and dependency upon civilian mining, milling, and enrichment companies and associated regulations and hindrances derived from treaties, executive orders, and presidential administration precedence. With no fissile material, criticality issues are nonexistent and licensing challenges would be less burdensome than with a reactor. Furthermore, although reactors used to produce tritium could potentially be subject to casualty scenarios (LOCA, station blackout, and so on) thereby endangering personnel, facilities, and the environment, accelerators suffer no such hazards. Lower amounts of radioactive waste would be produced and personnel would be subject to lower amounts of ionizing radiation (maintaining ALARA).

However, APT is indeed a new and experimental technology and, for this reason, "DOE did not pursue development of the accelerator concept because it did not believe sufficient time existed to develop the concept, given the immaturity of the technology."[54] Because of the exigency of tritium, DOE decided that further pursuit of APT was not justified.

---

[51] G.P. Lawrence, "High Power Linear Accelerators for Tritium Production and Transmutation of Nuclear Waste," Denton, Texas: Los Alamos National Laboratory, 1990, http://www.osti.gov/energycitations/servlets/purl/6541091-0991EJ/6541091.pdf.

[52] Alan, Munter, ed., "Neutron scattering lengths and cross sections"

[53] GAO (U.S. Government Accounting Office), "NUCLEAR SCIENCE - Consideration of Accelerator Production of Tritium Requires R&D," June 1992, http://www.gao.gov/assets/220/216452.pdf.

[54] Ibid.

Also, cost estimates vary widely for undertaking this approach. A Los Alamos Executive Report from 1989 claims that "[t]he capital cost of the…APT design is estimated to about $2.3B (1988$USD)…[and] includes the accelerator, target building, and supporting facilities, as well as tritium recovery facilities"[55] [$4.5B 2012$USD]. This estimate does not include significant electrical costs to run such an accelerator, which may require purchasing or building a coal or natural gas power plant. Offering a differing assessment, a U.S. General Accounting Office study from 1991 claims that DOE (and its contractor) estimated the cost of building an APT system to be $5.3B (1989$USD) [$9.9B 2012$USD].[56] A CRS Report in 1997 called for $5.4B 1997$USD for "actual construction"[57] [$7.8B 2012$USD]. Cost estimates from various government entities vary considerably and reach into the billions of dollars. The general estimate is that APT may require more initial capital investment than existing methods.

Although APT offers several significant advantages over reactor-produced tritium, future use of the technology in the short-term timeframe seems unlikely. Scientific endeavors involving APT will most likely remain in the R&D and "proof of concept" phases for the near future. In addition, Congressional hesitancy to fund large new ventures in the NW complex will likely prevent future large-scale investment into APT. In the long term, as R&D matures and if short-term tritium production methods prove to be unsustainable, large-scale use of APT could be reexamined.

Modular High-Temperature Gas-cooled Reactor (MHTGR)

The modular MHTGR reactor represents a design choice for a significantly low-power, physically smaller unit. The graphite-moderated, typically helium-cooled (although other choices may be available) reactor is often touted for its inherently or passively safe protection systems.

Lithium aluminate spheres are coated in carbon-related compounds (i.e., silicon carbide and others) and aggregated into a target element assembly. Subjected to a neutron flux, the lithium reaction produces tritium inside the coated spheres. Tritium has been shown to diffuse through the sphere's coatings, but significant amounts remain captive inside. Special facilities would be necessary to handle the irradiated target assemblies and extract the tritium from the spheres. [58]

In 1988 the then-Secretary of Energy suggested that a new $3.6B (1988$USD) [$7.0B 2012$USD] MHTGR built at INL could be used for tritium production for national security needs. In 1992 the DOE cancelled the gas-cooled reactor program and has made no plans to restart.[59]

Likelihood of Future Use - MGTGR

The U.S. has had two commercial gas-cooled reactors (though not modular) in the past (Peach Bottom and Fort St. Vrain), but both are currently shut down. [60] As a result, there is very little design and operational experience with gas-cooled reactors in the U.S., a fact that contributes to the low likelihood of future utilization.

---

[55] Los Alamos National Laboratory and Brookhaven National Laboratory, March 1989, *Accelerator Production of Tritium (APT): Executive Report*.

[56] GAO (U.S. Government Accounting Office), *Accelerator Technology for Tritium Production Needs Further Study*, October 1991, http://gao.justia.com/department-of-energy/1991/10/nuclear-science-rced-92-1/RCED-92-1-full-report.pdf.

[57] Richard E. Rowberg and Clifford Lau, "The Department of Energy's Tritium Production Program," September 1998, University of North Texas Digital Library, http://digital.library.unt.edu/ark:/67531/metacrs752/.

[58] Sandra Lee Harms, *Modeling Tritium Release from Triso-coated NP-MHTGR Target Particles*, (master's thesis, MIT, 1992), http://dspace.mit.edu/bitstream/handle/1721.1/72766/27457562.pdf?sequence=1.

[59] J.T. Maki, *et al.*, *NP-MHTGR Fuel Development Program Results*, Idaho National Laboratory, October 2002, http://www.inl.gov/technicalpublications/Documents/2699518.pdf.

[60] NRC (U.S. Nuclear Regulatory Commission), *Preapplication Safety Evaluation Report for the Modular High-Temperature Gas-Cooled Reactor (MHTGR)*, December 1995, http://www.inl.gov/technicalpublications/Documents/2699518.pdf.

Liquid Metal Reactor (LMR) / Molten Salt Breeder Reactor (MSBR)

Although there is less experience pertaining to liquid metal reactor (LMR) operation and fewer LMRs exist, LMRs represent an additional means of tritium production.

Some LMRs are designed to operate at a high flux. This characteristic can be used to efficiently convert Li-6 into tritium in the process described previously. In addition, an LMR can be designed to use lithium (or some metallic alloy containing lithium) as a coolant. Producing 20 to 50 times the amount of tritium than in an LWR coolant is an inadvertent side effect. This tritium will need to be removed from the coolant to maintain low personnel exposure so the potential exists to capture this byproduct for side uses.[61]

The Fast Flux Test Facility (FFTF) is a sodium-cooled fast neutron reactor at the DOE's Hanford Site and may be available for tritium production with some retrofitting. Originally designed as an experimental facility to test revolutionary materials and fuels for the DOE with application to the commercial nuclear industry, the FFTF's main characteristic is that it was designed to operate with a high flux, which can be used to irradiate tritium precursors and produce tritium. It was decided in 1993 to deactivate FFTF, but legal battles over the next 20 years have alternately mandated and inhibited various stages of this process. In 2003, it was placed in cold standby with the remaining sodium drained in 2005 by drilling holes in the core support basket. While a significant hurdle to be overcome since operation could not resume in this current state, it may still be possible to restart the facility in a timely, cost-efficient manner because the core itself is intact. FFTF was placed in a long-term storage condition in 2009, but it is uncertain what exactly that entails or what would be required to restart. It is estimated that building a similar facility would cost \$2B to \$5B (2012\$USD).[62]

The DOE concluded in 1998 that the government lacked a sufficient quantity of unencumbered plutonium to fuel FFTF beyond approximately 18 months.[63] Significant quantities of potentially-useful plutonium have been prohibited from NW use. FFTF could be fueled with HEU; yet, previous concerns of limited HEU stores arise. Because the HEU option dictates a lower tritium production rate, DOE does not think that a sufficient amount would be produced to meet the needs of the stockpile.[64] Furthermore, "the use of HEU would run counter to U.S. policy to minimize the use of this fuel globally."[65] There exists the technological feasibility of using FFTF for tritium production, but additional limiting factors cannot be overlooked.

Likelihood of Future Use – LMR / MSBR

No reactors using a lithium coolant currently exist in the U.S. Also, very little experience involving lithium-cooled reactors has been obtained. The chances of a reactor of this type being built for the production of tritium appear unlikely.

---

[61] Roy C. Robertson, *Conceptual Design Study of a Single-Fluid Molten-Salt Breeder Reactor*, Oak Ridge National Laboratory, June 1971, http://www.osti.gov/bridge/servlets/purl/4030941/4030941.pdf.

[62] DOE (U.S. Department of Energy), "400 Area/Fast Flux Test Facility," October 28, 2012, http://www.handford.gov/page.dfm/400AreaFPTF.

[63] DOE (U.S. Department of Energy), Nonproliferation Implications of Alternative Tritium Production Technologies

[64] Ibid.

[65] Ibid.

Conclusion

Tritium is an indispensable component of the U.S. NW stockpile. As a perishable substance, an assured production method is needed to avoid any shortfalls in future supplies. Several options have been outlined with most subject to political, financial, legal, or technological limitations. The future of tritium production for U.S. national security purposes remains ambiguous; an analysis of potential options has yielded several plausible paths forward.

The most likely near-term path for tritium production is the continued use of TVA's Watts Bar I reactor. The finite stores of LEU enriched by USEC prior to closing out PGDP most likely represent the last unencumbered fuel for Watts Bar I. As significant uncertainty surrounds the necessity of using domestically-enriched uranium to fuel reactors to produce tritium, future sources of LEU remain unclear.

Downblending existing stores of government-owned HEU represents perhaps the least financially taxing method of producing LEU for Watts Bar I. The continued use of PGDP at a cost of hundreds of millions of dollars would be required, but this option would cost significantly less than constructing a new facility at a cost likely totaling in the billions. The mechanism by which presidential guarantees never again to use the particular stores of HEU for weapons purposes would be removed is unknown. Although possibly the least financially taxing option, removing these promises would surely incur some political cost. Also, it is unknown to what degree employing this option would endanger stores of HEU reserved for naval reactor use.

The option incurring the least cost politically may be the reenrichment of unencumbered, depleted uranium tails. Free from politically sensitive or ambiguous restrictions, the breaking of presidential guarantees or international agreements would not be required under this option, but reenrichment would most likely have to occur at PGDP at a significant financial cost.

The financial and political backing of USEC's ACP represents a difficult dilemma for decision makers. If the need for domestic enrichment of uranium for tritium production is deemed to be unnecessary, then this backing is unwarranted. However, if this requirement is upheld or officially justified, decision makers will need to back ACP as the only domestic enrichment option currently available, perhaps at a significant personal political cost. Furthermore, additional R&D funding for USEC or the approval of the long-sought loan guarantee would become necessary.

The best option may be to construct a wholly government-owned reactor. DOE has a significant history of operating reactors for defense purposes. As the TEF is currently located at the SRS, siting a reactor on the same grounds may maximize efficiency. While a PWR similar to commercial generating stations might be appealing, procuring unencumbered LEU for fuel may still pose a challenge. Historical experience using HWRs at SRS should not be overlooked; perhaps HWRs could be used again taking advantage of modern technology. Ultimately, this option would very likely represent a significant cost and legislative support may be difficult to garner. Though this is the most secure way to assure uninterrupted tritium production for national defense needs, a purpose-built reactor would likely face political and financial hurdles.